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Towards Earth System Modeling: Coupled Ocean Forecasting

Ségolène Berthou[1], John Siddorn[2], Vivian Fraser-Leonhardt[1], Pierre-Yves Le Traon[3], Ibrahim Hoteit[4]

[1]MetOffice, Exeter, UK
[2]Data, Science and Technology, National Oceanography Centre, Southampton, UK
5 [3]Mercator Ocean International, Toulouse, France
[4]Physical Science and Engineering Division, King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia

Correspondence to: Ségolène Berthou (segolene.berthou@metoffice.gov.uk)
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Abstract. Modelling our planet is challenging, and forecasting the ocean component is crucial for better understating physical processes in a changing climate. To achieve this objective, numerical ocean models require more advanced approaches that aim at connecting different Earth system's components in a more sophisticated way: this is offered by coupling methods, that
15 involve exchanging information between discrete modelling systems. The paper explains the principles of two-way coupling, where models run simultaneously and exchange information both ways. As individual models reach better accuracy, coupling becomes a key factor to improve forecasting capability because it reproduces the natural complexity of the environment: a wealth of literature shows the benefits of coupling. However, coupling is still limited in operational oceanography by its large demands on computational resources, by data assimilation techniques (currently not very well harmonized between the
20 different models) and by administrative separation of forecasts across different earth-system components. Overcoming these barriers will support ocean predictions towards a multi-hazard approach and a more accurate representation of the Earth systems' components interaction, and improve collaborations between multi-disciplinary forecasting communities.

1 Introduction

Coupling can be loosely defined as the process of exchanging information between discrete modelling systems, generally of
25 components of the earth system, to better represent exchange processes (Shapiro et al., 2010). The number of components of a coupled system, and indeed the level of coupling between the components, varies depending on the application. Coupled global climate models (GCMs) generally include the ocean, ice, atmosphere and land surface. Increasingly surface waves are included to represent the exchange between the ocean and the atmosphere better, especially for applications that require representation of natural hazards such as storms. For earth-system models which need to include predictions of the biogenic
30 components to predict carbon and other nutrient transfers the components are often extended to include ocean biogeochemistry and atmospheric chemistry (Mulcahy et al., 2023).

There are a number of solutions to how this coupling may be achieved, and which is preferred will depend both on the scientific importance of the exchanges and the timescales on which they occur and on technical limitations. In the "traditional" way of

working the models are run independently with a flux of information from adjacent components of the earth system being
35 calculated based on independent and non-interactive models. This implies that the winds, precipitation and air temperatures
("forcing") used to drive the exchanges at the ocean's surface do not respond to changes in the ocean conditions themselves.
The forcing is not calculated on a timestep basis but over a period generally somewhere between an hour and a day. Forecasts
run in this mode are termed forced or one-way coupled.

Coupled systems exist with varying complexity of exchanges between models. For example, a common approach for the
40 coupling of hydrodynamics and sea ice is to run both systems at the same time and exchange information both ways. These
are termed fully or two-way coupled systems. In these two-way coupled systems, the independent models often communicate
with each other through an interface code ("coupler") which allows the independent models to operate on different grids and
with different timesteps (Valcke, 2013). As the number of components interacting with each other increases the flexibility of
including a coupler becomes increasingly attractive. Figure 1 illustrates the Regional Environmental Prediction system under
45 development in the United Kingdom, with complex exchanges between five different models.
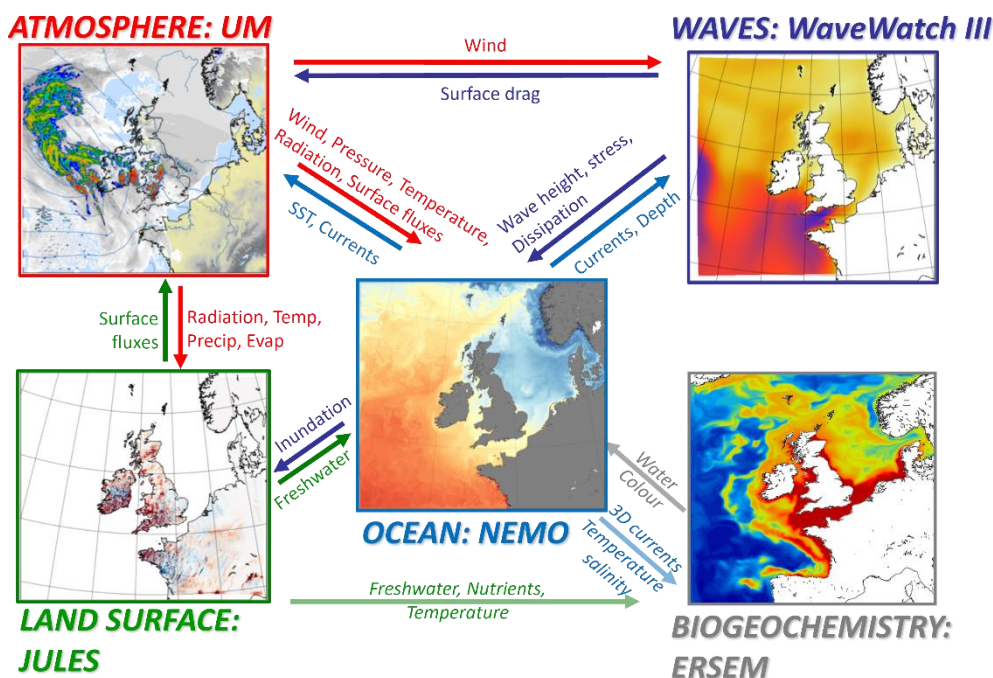
Figure 1: Regional coupled system under development in the United Kingdom for in the Regional Environmental Prediction
project (Lewis et al., 2019), bringing together all the models run by the Met Office for short-term predictions and climate
50 projections. Arrows represent exchanges between models – either as integrated coupling at the time-step (UM/JULES), 2D
coupling through the OASIS coupler (Valckle et al. 2013) (UM / WaveWatch III / NEMO) or 3D coupling through the FABM
coupler (NEMO/ERSEM).

2 Why is coupling important for Ocean Prediction?

Atmosphere / ocean coupling is common practice at the seasonal and decadal timescales. At these scales, most of the memory
55   is contained in the ocean and in coupled interactions, such as for the El Nino Southern Oscillation (ENSO). Indeed, both the
ocean and atmosphere can propagate an anomaly in the other component to remote places. For example, oceanic equatorial
waves generated by wind anomalies can propagate to the whole tropical Pacific and generate an El Nino event, and in turn the
atmosphere may generate teleconnections from the tropics to the mid-latitudes through upper-level Rossby wave trains in the
troposphere or planetary waves in the stratosphere, and influence the ocean back in remote ocean basins (Hardiman et al.,
60   2019; Kim et al., 2012). These may take longer than 10-days to propagate and are therefore sources of seasonal and multi-
annual forecast signals. For short-term marine prediction, coupling is emerging as a new potential for improving both
atmospheric and oceanic predictions (Brassington et al., 2015).

A clear and extremely well documented weather situation when air-sea coupling is key for both atmosphere and ocean are
tropical cyclone forecasts: the strength of tropical cyclones is decreased through large decreases in SST caused by intense
65   turbulent fluxes, deepening of the surface mixed layer by entrainment (Vellinga et al., 2020; Mogensen et al., 2017; Castillo
et al., 2022; Feng et al., 2019) and (if the cyclone translation speed is slow) by upwelling (Corale et al., 2023; Yablonsky et
al., 2009). In more general situations, coupling reduces the lifetime of mesoscale eddies and dampens submesoscale currents
through dampening of the wind stress curl and heat fluxes (Yang et a., 2019; Renault et al., 2016; Renault et al., 2018; Dawe
and Thompson, 2006). Coupling also sometimes involves a higher resolution atmosphere than forcing, which then results in
70   more turbulent eddy kinetic energy in the ocean (Storto et al., 2023). In the tropics, dynamical waves in the atmosphere and
ocean can influence each other. For example, Madden Julian Oscillation (MJO) atmospheric events in the Indian Ocean can
be modulated by coupling (Fu et al., 2017) or simply by the diurnal cycle of SST (Karlowska et al., 2023). Convectively
Coupled Kelvin waves also generate a strong signal in the Indian ocean (Azaneu et al., 2021).

At the coastal scale, coupling also becomes interesting since the assumptions of equilibrium between earth system components
75   often break down (e.g. wave state is not in equilibrium with winds in the sheltered North Sea - Grayek et al., 2023; Wiese et
al., 2019; Whale et al., 2017). Some examples in the literature include better near-surface currents and upwelling forecasting
with the inclusion of the Stokes-Coriolis drift by a wave model, which induce an extra term of advection in the direction of
wave group speed (Alari et al., 2016; Bruciaferri et al., 2021). Coupling also benefits wave modelling, for example where tidal
currents modulate wave and wind activity (Renault et al., 2022; Valiente et al., 2021). Coupling an ocean with waves can have
80   considerable impacts on SSTs, which can go in either direction, depending on the difference in momentum stress passed to the
ocean (more momentum input by the waves in the case of Lewis et al. (2019), resulting in a near-surface cooling, but less
momentum in Alari et al. (2016), resulting in warming), through modulation of the ocean stratification. Coupling a wave model
with an atmospheric model will tend to decrease wind speed over young seas and increase ocean momentum flux, especially
important during storms (Gentile et al., 2022; Bouin and Lebeaupin Brossier, 2020). In general, coupling will tend to dampen
85   air-sea fluxes because components will tend to adjust to one another, so this may decrease ocean spread at the start of ensemble

forecasts (Lea et al., 2022). However, the spread in SST will increase rapidly in regions which have a shallow surface mixed layer, which respond quickly to atmospheric spread (Lea et al., 2022). Precipitation and river flows can also have a local influence on near-surface temperatures and salinity in the ocean, especially during extreme precipitation events (Bouin et al., 202; Sauvage et al., 2018). The ocean can finally act as memory between two intense atmospheric events (e.g strong winds,

90 and strong precipitation (Berthou et al., 2016; Lebeaupin Brossier et al., 2012) or in the case of marine heatwaves and extreme temperature or precipitation event (Berthou et al., 2024; Martín et al., 2024), in which cases a coupled system is beneficial for longer range forecasting. In regional atmospheric forecasts, using a predicted SST (either obtained through coupling or forcing) is beneficial for variables such as near-surface temperature (Mahmood et al., 2021), fog (Fallmann et al., 2019) or snow (Yamamoto et al., 2011).

95 However, it is worth noting that differences in near-surface parameterisations can also generate differences which are as large or larger than coupling differences (Gentile et al., 2022), indicating the need for continuous research and investment in observation systems of near-surface characteristics. Coupling is most successful when the water, heat and momentum budgets are closed, which can be challenging when model parameterisations are designed in forced mode. Recent parameterisation improvements taking into account coupled variables include wave coupling in the NEMO Turbulent Kinetic Energy scheme

100 (Couvelard et al., 2020), or current feedback taken into account in atmospheric turbulence (Renault et al., 2019), or finally the new Wave-Age dependent Stress Parameterisation (Bouin et al., 2024)). In some situations, increasing the complexity of air-sea exchanges can be beneficial, for example including sea spray effects on moisture and heat fluxes (Yang et al., 2019; Xu et al., 2021; Zhang et al., 2005; Bianco et al., 2011).

Coupling with land and river models are also attractive to provide river-flow forecasts, especially as the coupling interface

105 gets more complex, to include back-water effects into rivers and coastal wetting and drying (Bianco et al., 2011). Finally, coupling with biogeochemistry and sediment transport models can provide interesting feedback on the ocean color, with a feedback loop between thermal stratification and phytoplankton bloom, through the modulation of depth penetration of the solar heat flux (Skákala et al., 2022). Other feedbacks include chemistry and aerosols, where the atmosphere can then provide deposition fluxes (e.g. iron, nitrogen) to the ocean, and the phytoplankton sends back chemicals which can affect low-level

110 cloud cover (Mulcahy et al., 2023).

The potential benefits of using a coupled framework are also reinforced by the move towards a multi-hazard approach to predictions. Natural hazards from multiple sources may combine or occur concurrently. Large waves, storm surges, high-wind speeds, and extreme precipitation are all hazards that are likely to co-occur, and influence each other through coupled feedbacks that can compound one another (for example through over-topping). Coupled systems that predict these feedbacks may enable

115 an improvement in the range and consistency of actionable information to be provided through hazard warnings and guidance.

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3 How extended is the use of coupled modelling for Ocean Prediction?

Many centers have developed monitoring and prediction tools independently for individual Earth components (e.g. atmosphere, ocean, land, waves, etc.). This is natural based on the historical context of their development and limitations on computing capabilities, but it has created an infrastructure within and across institutions that adds complexity to the task of
120 unifying prediction systems. The major prediction centers are making progress towards an integrated approach by unifying software infrastructure for models and data assimilation capabilities (see for example Guiavarc'h et al., 2019; Allard et al., 2012; Komaromi et al., 2021), as well as providing opportunities to increase interactions among the development teams of each system component. Part of this unifying framework, and the most usual approach, is the use of coupling software. This software creates a computational interface between separate systems that allows the passing of information between them
125 without undue intrusion into the code of the modelling systems. This approach is widely used (e.g. Lewis et al., 2018; Pianezze et al., 2022; Wahle et al., 2017) but other approaches are also being used or developed. ECMWF (Wedi et al., 2015) take a different approach and have integrated their various modelling components into a single executable with the passing of information being done internally within the code rather than through a separate coupling software.

The extent to the uptake of coupled modelling is still largely limited, however, by several barriers. First, it places extreme
130 demands on computational resources: the cost of running an extra model is often prohibitive for agencies with limited forecasting remits (e.g. only ocean forecasting). However, recognising the benefits acknowledged above, these agencies are exploring alternatives, such as coupling with a single-column mixed layer model, either in the atmosphere or the ocean (Voldoire et al., 2017; Lemarié et al., 2021). For the agencies with several remits (e.g. weather, marine, hydrology, air quality forecasting), coupled modelling is more attractive and has the potential to reduce the complexity of the modelling chains, as
135 well as prevent large data transfers between platforms. The perspective of seamless predictive capability (Ruti et al, 2020), especially important during impactful extreme cyclonic or convective events, means km-scale regional coupled systems are actively being developed in several centres (Sauvage et al., 2021; Lewis et al., 2019; Corale et al., 2023; Castillo et al., 2022). A second major barrier is data assimilation, which requires the processing of environmental observations, is itself a technically challenging problem which is made harder if you try and harmonise that across all the earth system components. The bigger
140 challenge comes when doing coupled data assimilation itself; data assimilation requires the calculation of an innovation (difference between the modelled and observed value) and then appropriately adjusting the model parameter space to create a state estimate that is optimised to best reflect understanding of model and observation errors. In coupled systems there are correlations between parameters in the different systems that need to be respected: for example, sea surface and air surface temperature are closely correlated. This creates an additional scientific and technical challenge that needs to be addressed in
145 coupled forecasting systems (Penny and Hamill, 2017).

Weaker barriers include the need for different frequency of running forecasts: ocean forecasts often run daily with a single deterministic member but the atmospheric and the wave forecasts require sub-daily ensembles with several members. In ensemble modelling, inflated spread schemes are often employed (e.g. in the SST), and generate a much larger spread than the

ocean uncertainty, and must be modified in coupled systems (Lea et al., 2022). Finally, simple bureaucratic barriers such as
150 the constraint of a common forcing model in international projects can also prevent the adoption of coupled modelling.

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STATE OF THE
PLANET
Discussions

315   Zhang, L., Zhang, X., Perrie, W., Guan, G., Dan, B., Sun, C., Wu, X., Liu, K., Li, D.: Impact of Sea Spray and Sea Surface

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320   **Data and/or code availability**

Not applicable.

Authors contribution

JS started a draft of this document, SB took over and completed the article, helped with a literature review completed by VFL.

PYLT, IH reviewed the text.

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This will be included at a later stage.